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Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology

V.V. Tyagi[a,*], S.C. Kaushik[a], S.K. Tyagi[b]

[a] Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
[b] Sardar Swaran Singh National Institute of Renewable Energy Wadala Kalan, Kapurthala, Punjab 144610, India

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ABSTRACT

This article presents an overview on the research and development and application aspects for the hybrid photovoltaic/thermal (PV/T) collector systems. A major research and development work on the photovoltaic/thermal (PVT) hybrid technology has been done since last 30 years. Different types of solar thermal collector and new materials for PV cells have been developed for efficient solar energy utilization. The solar energy conversion into electricity and heat with a single device (called hybrid photovoltaic thermal (PV/T) collector) is a good advancement for future energy demand. This review presents the trend of research and development of technological advancement in photovoltaic thermal (PV/T) solar collectors and its useful applications like as solar heating, water desalination, solar greenhouse, solar still, photovoltaic–thermal solar heat pump/air-conditioning system, building integrated photovoltaic/thermal (BIPVT) and solar power co-generation.

Contents

* Corresponding author. Tel.: +91 11 26596465.
E-mail address: vtyagi16@gmail.com (V.V. Tyagi).

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1. Introduction

Energy is considered a prime agent in the generation of wealth and a significant factor in the economic development of any country and the living standard of people. The importance of energy in economic development is recognized universally and historical data verify that there is a strong relationship between the availability of energy and economic activity. With the increasing demand of energy, today the world daily oil consumption is 85 million barrels of crude oil [1]. Despite the well-known consequences of fossil fuel combustion on the environment, this is expected to increase to 123 million barrels per day by the year 2025 [2]. This is the main reason for pollution.

The greatest advantage of solar energy as compared with other forms of energy that is environmental friendly and abundantly available and can be supplied without any environmental pollution. Over the past century fossil fuels have been provided most of our energy needs because these are much cheaper and more convenient than energy from alternative sources, and until recently environmental pollution has been of little concern. Hybrid systems for solar (renewable) energy utilization have attracted considerable attention from scientists and engineers during the last decade because of their higher efficiency and stability of performance in comparison to individual solar devices. Traditionally, devices intended for using solar energy fall into two main classes depending on the method of its conversion: either heat or electricity, like thermal collectors and photovoltaic modules respectively.

Solar thermal energy collectors are special kind of heat exchangers that convert solar radiation into thermal energy through a transport medium and/or moving fluid. Classification of various solar collectors are illustrate in Fig. 1. The major component of any solar system is the solar collector. This is a device which absorbs the incoming solar radiation, converts it into heat energy, and transfers it through a fluid (usually air, water, or oil) for useful purpose/applications. Generally, they are used as air dryer/heater for drying the agricultural products and/or heating/cooling applications in combination with the auxiliary heaters for air conditioning of buildings.

Photovoltaic (PV) is the most useful way of utilizing solar energy by directly converting it into electricity. Energy conversion devices, which are used to convert sunlight to electricity by the use of the photoelectric effect are called solar cells. A photovoltaic system consists of solar cells and ancillary components. It converts the solar radiation directly into electricity. In 1954, researchers at the Bell Telephone Laboratories demonstrated the first practical conversion of solar radiation into electric energy by use of a p–n junction type solar cell with 6% efficiency [3]. With the advent of the space program, photovoltaic cells made from semiconductor-grade silicon quickly became the power source of choice for use in satellites. The common solar power conversion efficiencies are between 15 and 20% [4].

However, today a new area has emerged incorporating both the methods of energy conversion, which can be called photo thermo-conversion [5]. The solar energy conversion in to electricity and heat with a single device called hybrid photovoltaic thermal collector (PVT). In this way, heat and power are produced simultaneously and it seems a logical idea to develop a device that can comply with both demands. A novel approach for research development in PV–thermal system is described in this paper.

2. Solar thermal collectors

Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. There are basically two types of solar collectors: non-concentrating or stationary and concentrating. A non-concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux. A large number of solar collectors are available in the market. A comprehensive list is shown in Table 1 [6]. In this section a review of the various types of collectors currently available will be presented. This includes flat plate collector (FPC), evacuated tube collector (ETC), and concentrating collectors.

2.1. Flat plate collector

The flat plate collector (FPC) is the heart of any solar energy collection system designed for operation in the low temperature range (less than 60 °C) or in the medium temperature range (less

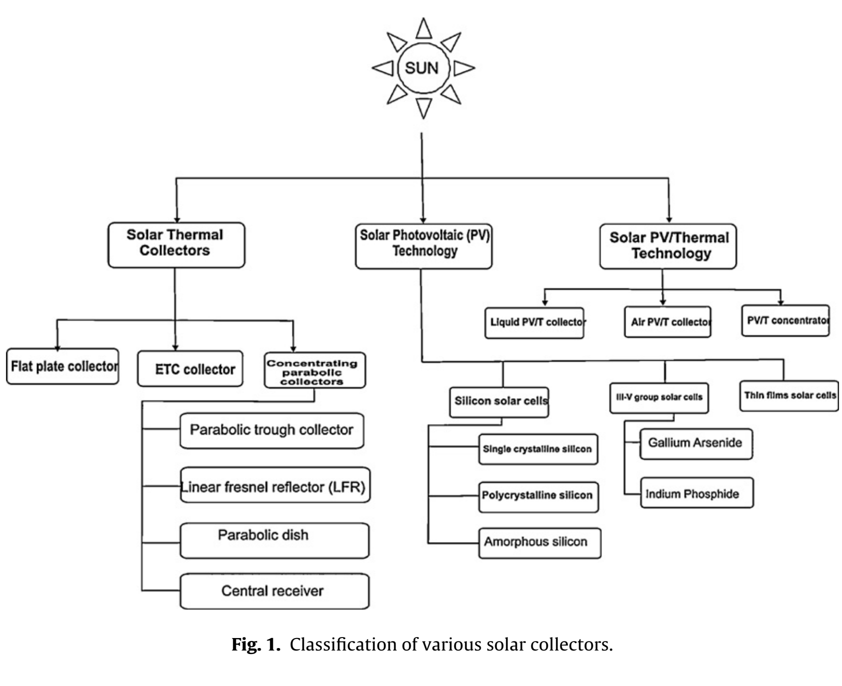

Fig. 1. Classification of various solar collectors.

Table 1
Types of solar thermal collectors.

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Parabolic trough collector (PTC)	Tubular	15–45	60–300
	Cylindrical through collector (CTC)	Tubular	10–50	60–300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150–2000

than 100 °C). It is used to absorbed solar energy, convert it into heat and then to transfer that heat to stream of liquid or gases. Flat-plate solar collectors, being mechanically simpler than concentrating collectors, are mainly used for domestic and industrial purposes [7–11]. The essential features of the conventional flat plate collectors are:

(i) A flat blackened absorbing plate (normally metallic) upon which the solar radiation falls and gets absorbed, thus changing to thermal energy.
(ii) Tubes, channels or passages attached to the blackened absorber plates to circulate the fluid required to remove the thermal or heat energy from the plate.
(iii) Insulation which is provided at the back and sides of the absorber plate to minimize conductive heat losses.
(iv) A transparent cover (one or two sheets) of glass or plastic to reduce the upward convection and radiation heat losses from the absorber plate.
(v) A weather tight container which encloses the above components.

FPC is usually permanently fixed in position and requires no tracking of the sun. The collectors should be oriented directly towards the equator, facing south in the northern hemisphere and north in the southern. The optimum tilt angle of the collector is equal to the latitude of the location with angle variations of 10–15 °C more or less depending on the application. A typical flat plate solar collector is shown in Fig. 2.

2.2. Evacuated tube collector

The evacuated tube solar collectors (ETC) provide the combined effects of a highly selective surface coating and vacuum insulation of the absorber element so they can have high heat extraction efficiency compared with flat plate collectors in the temperature range above 80 °C [12]. At present, the glass evacuated tube has become the key component in solar thermal utilization and they are proved to be very useful especially in residential applications for higher temperatures. So the evacuated solar collectors are widely used to supply the domestic hot water or heating, including heat pipe evacuated solar collectors and U-tube glass evacuated tube solar collectors [13–18]. ETC use liquid–vapor phase change materials to transfer heat at high efficiency. These collectors feature a heat pipe (a highly efficient thermal conductor) placed inside a vacuum-sealed tube. The pipe, which is a sealed copper pipe, attached to a black copper fin that fills the tube (absorber plate) is a metal tip attached to the sealed pipe (condenser). The heat pipe contains a small amount of fluid that undergoes an evaporating-condensing cycle. In this cycle, solar heat evaporates the liquid, and the vapor travels to the heat sink region where it condenses and releases its latent heat. The condensed fluid return back to the solar collector and the process is repeated. When these tubes are mounted, the metal tips up, into a heat exchanger (manifold). A schematic diagram of an evacuated tube collector is given in Fig. 3.

2.3. Concentrating collectors

Concentrating collectors provide energy at temperatures higher than those of flat plate and ETC collectors. They re-direct solar radiation passing through an aperture into an absorber and usually require tracking of the sun. In concentrating collectors solar energy is optically concentrated before being transferred into heat.

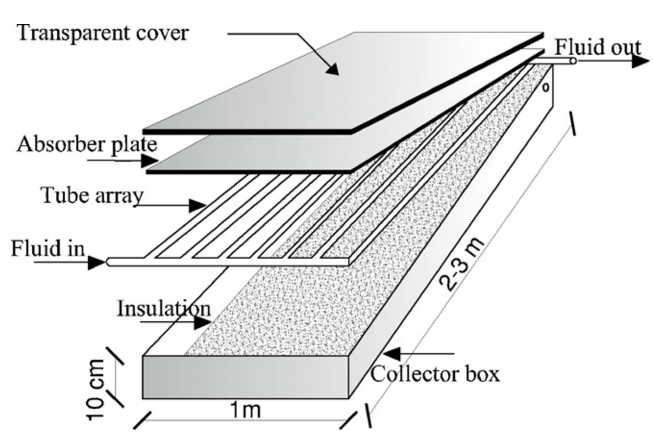

Fig. 2. Cross-section and isometric view of flat-plate collector.

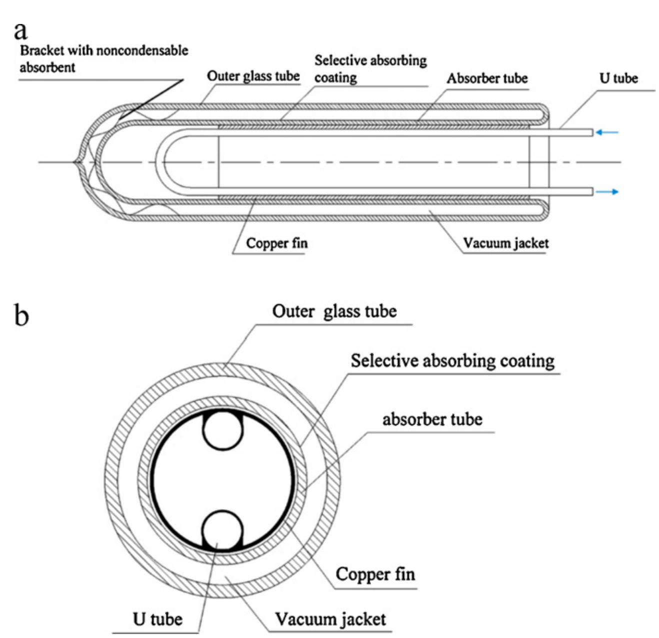

Fig. 3. Glass evacuated tube solar collector with U-tube. (a) Illustration of the glass evacuated tube and (b) cross section.

Table 2
Advantage and disadvantage of concentrating collectors.

S.no.	Advantages	Disadvantages
1.	The working fluid can achieve higher temperatures in a concentrator system when compared to a flat-plate system of the same solar energy collecting surface. This means that a higher thermodynamic efficiency can be achieved.	Concentrator systems collect little diffuse radiation depending on the concentration ratio.
2.	It is possible with a concentrator system, to achieve a thermodynamic match between temperature level and task. The task may be to operate thermoionic, thermodynamic, or other higher temperature devices.	Some form of tracking system is required so as to enable the collector to follow the sun.
3.	The thermal efficiency is greater because of the small heat loss area relative to the receiver area.	Solar reflecting surfaces may loose their reflectance with time and may require periodic cleaning and refurbishing.
4.	Reflecting surfaces require less material and are structurally simpler than FPC. For a concentrating collector the cost per unit area of the solar collecting surface is therefore less than that of a FPC.	
5.	Owing to the relatively small area of receiver per unit of collected solar energy, selective surface treatment and vacuum insulation to reduce heat losses and improve the collector efficiency are economically viable.	

Concentration can be obtained by reflection or refraction of solar radiation by the use of mirrors or lens. A concentrating collector exhibits certain advantages and disadvantages as compared with the conventional flat-plate type collector [19] some of them are given in Table 2.

Concentrating collectors can also be classified into non-imaging and imaging depending on whether the image of the sun is focused at the receiver or not. The concentrator belonging in the first category is the CPC whereas all the other types of concentrators belong to the imaging type. The collectors falling in this category are:

Parabolic trough collector.
Linear Fresnel reflector.
Central receiver.
Parabolic dish.

2.3.1. Parabolic trough collector (PTC)

The first practical experience with parabolic trough collector (PTC) goes back to 1870, when a successful engineer, John Ericsson, a Swedish immigrant to the United States, designed and built a 3.25-m^2-aperture collector which drove a small 373-W engine. Steam was produced directly inside the solar collector (today called direct steam generation or DSG). From 1872 to 1875, he built seven similar systems, but with air as the working fluid [20]. Nowadays, PTC target application in which a solar field can be successfully integrated for supplying thermal energy at temperatures up to 250 °C (Fig. 4). Nevertheless, there are other applications, such as heat-driven refrigeration and cooling, low-temperature heat demand with high consumption rates, irrigation water pumping, desalination and detoxification. On the one hand, these temperature requirements cannot be achieved by conventional low-temperature collectors

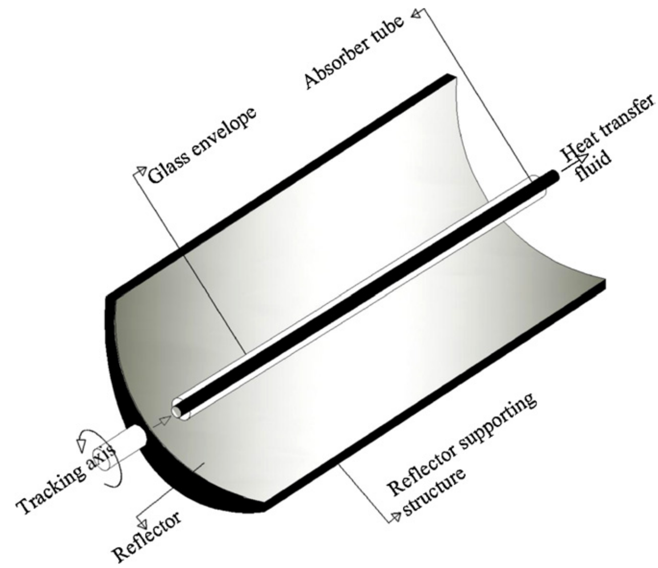

Fig. 4. Parabolic trough collector (PTC).

(flat plate collectors and evacuated tubes). On the other hand, use of solar concentrating systems with high concentration ratios and high-temperature absorbers would be unnecessarily expensive.

2.3.2. Linear Fresnel reflector (LFR)

The linear Fresnel reflector (LFR) differs from that of the parabolic trough collectors in that the absorber is fixed in space above the mirror field (Fig. 5). Also, the reflector is composed of many low row segments, which focus collectively on an elevated long tower receiver running parallel to the reflector rotational axis [21]. This system offers a lower cost solution as the absorber row is shared among several rows of mirrors. However, one fundamental difficulty with the LFR technology is the avoidance of shading of incoming solar radiation and blocking of reflected solar radiation by adjacent reflectors. Blocking and shading can be reduced by using absorber towers elevated higher and/or by increasing the absorber size, which allows increased spacing between reflectors remote from the absorber. Both these solutions increase costs, besides a larger ground usage is required. The compact linear Fresnel reflector (CLFR) offers an alternate solution to the LFR problem. The classic LFR has only one linear absorber on a single linear tower. This prohibits any option of the direction of orientation of a given

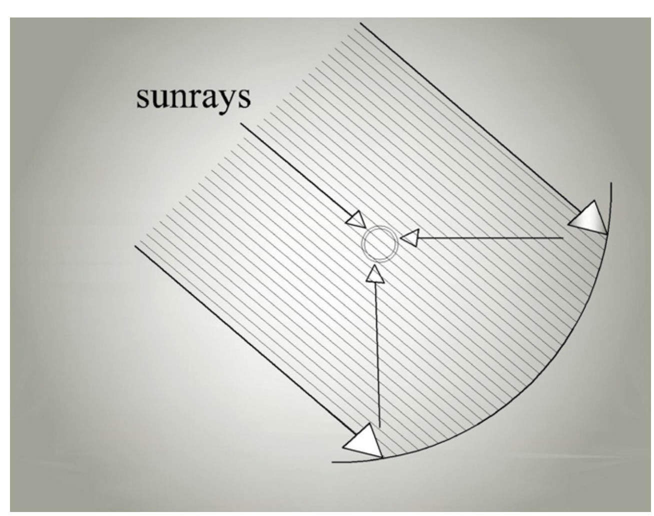

Fig. 5. Linear Fresnel reflector (LFR) collector.

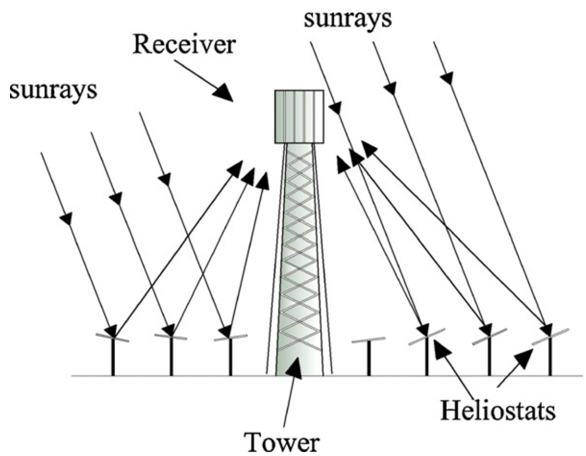

Fig. 6. Central receiver system.

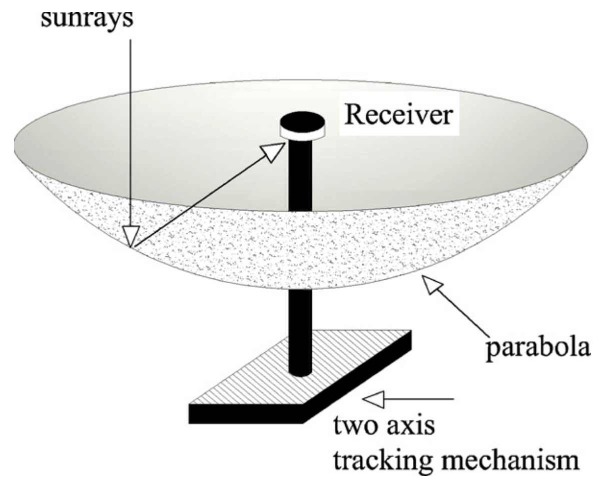

Fig. 7. Schematic of a parabolic dish collector.

reflector. Since this technology would be introduced in a large field, one can assume that there will be many linear absorbers in the system. Therefore, if the linear absorbers are close enough, individual reflectors will have the option of directing reflected solar radiation on to at least two absorbers. This additional factor gives potential for more densely packed arrays, since patterns of alternative reflector inclination can be set up such the closely packed reflectors can be positioned without shading and blocking solar radiation [22].

2.3.3. *Central receiver system*

The central receiver systems (Fig. 6) are considered to have a large potential for mid-term cost reduction of electricity compared to parabolic trough technology since they allow many intermediate steps between the integration in a conventional Rankine cycle up to the higher energy cycles using gas turbines at temperatures above 1000 °C, and this subsequently leads to higher efficiencies and huge outputs [23,24]. Another alternative is to use Brayton cycle (gas, turbines, which require higher temperature than the ones employed in Rankine cycle). There are three general configurations for the collector and receiver systems. In the first, heliostats completely surround the receiver tower, and the receiver, which is cylindrical, has an exterior heat-transfer surface. In the second, the heliostats are located north of the receiver tower (in the northern hemisphere), and the receiver has an enclosed heat-transfer surface. In the third, the heliostats are located north of the receiver tower, and the receiver, which is a vertical plane, has a north-facing heat-transfer surface.

2.3.4. *Parabolic dish*

A parabolic dish reflector, shown schematically in Fig. 7, is a point-focusing collector. Concentrating solar energy onto a receiver located at the focal point of the dish, it tracks the sun in two axes. The dish structure must track fully the sun to reflect the beam into the thermal receiver. Parabolic-dish systems can achieve temperatures in excess of 1500 °C. Because the receivers are distributed throughout a collector field, like parabolic troughs, parabolic dishes are often called distributed-receiver systems. Parabolic-dish systems that generate electricity from a central power converter collect the absorbed sunlight from individual receivers and deliver it via a heat-transfer fluid to the power-conversion systems.

3. Solar photovoltaic (PV) technology

Photovoltaics (PV) comprise the technology to convert sunlight directly into electricity. The term "photo" means light and "voltaic," electricity. A photovoltaic (PV) cell, also known as "solar cell," is a semiconductor device that generates electricity when light falls on it. When sunlight strikes a PV cell, the photons of the absorbed sunlight dislodge the electrons from the atoms of the cell. The free electrons then move through the cell, creating and filling in holes in the cell. It is this movement of electrons and holes that generates electricity. The physical process in which a PV cell converts sunlight into electricity is known as the photovoltaic effect. A photovoltaic system consists of solar cells and ancillary components. Fortunately the supply of energy from the sun to the earth is gigantic: 3×10^{24} J a year, or about 10,000 times more than that the global population currently consumes. In other words, covering 0.1% of the earth's surface with solar cells with an efficiency of 10% would satisfy our present needs [25]. In 1954, researchers at the Bell Telephone Laboratories demonstrated the first practical conversion of solar radiation into electric energy by use of a p–n junction type solar cell with 6% efficiency [26]. With the advent of the space program, photovoltaic cells made from semiconductor-grade silicon quickly became the main power source for use on satellites. The common solar power conversion efficiencies are between 15 and 20% [26]. However, the relatively high cost of manufacturing these silicon cells has prevented their widespread use. Another disadvantage of silicon cells is the use of toxic chemicals in manufacture. These aspects prompted the search for environmentally friendly and low cost solar cell alternatives.

3.1. *Types of solar cell*

Several different semiconductor materials have been used to make the layers in different types of solar cells, and each material has its own quantities and drawbacks. The first requirement of a material to be suitable for solar cell application is a band gap matching to solar spectrum. The band gap should be between 1.1 and 1.7 eV. The material must also have high motilities and lifetime of charge carriers. Other requirements are (i) direct band structure, (ii) consisting of readily availability, (iii) non-toxicity, (iv) easy reproducible deposition technique, (v) suitable for large area production, (vi) good photovoltaic conversion efficiency and (vii) long term stability The highest efficiencies achieved using the different semiconductor materials are given in Table 3 [27]. Depending on the material used solar cells can be categorized into three main groups:

- Silicon solar cells.
- III-V group solar cells.
- Thin films solar cells.

Table 3
Best efficiencies reported for the different types of solar cell.

Cell type	Highest reported efficiency for small area produced in the laboratory	Highest reported module efficiency
c-Si (crystalline Si)	24.7% (UNSW, PERL)	22.7% (UNSW/Gochermann)
Multi-c-Si	20.3% (FhG-ISE)	15.3% (Sandia/HEM)
αSi:H, amorphous Si	10.1% (Kaneka), N.B. single junction	Triple junction. Stabilized efficiency = 10.4%
μc-Si/αSi:H (micro-morph cell)	11.7% (Kaneka), N.B. minimodule	11.7% (Kaneka), N.B. minimodule
HIT cell	21% (Sanyo)	18.4% (Sanyo)
GaAs cell	25.1% (Kopin)	Not relevant
InP cell	21.9% (Spire)	Not relevant
GaInP/GaAs/Ge multijunction	32% (Spectolab), N.B. 37.3% under concentration	Not relevant
CdTe	16.5% (NREL)	10.7% (BP Solarex)
CIGS	19.5% (NREL)	13.4% (Showa Shell), N.B. for copper gallium indium sulfur selenide
Dye sensitized cell	8.2% (ECN)	4.7% sub-module (INAP)

3.1.1. Silicon solar cells

3.1.1.1. Single crystalline silicon. Solar cells are capable to converting sunlight into electricity directly. Among the many materials available for solar cells, the most widely used semiconductor in solar cells is single-crystal silicon. Silicon is the most promising because it is an abundant and safe raw material that has the potential for high efficiency performance. In particular, a-Si has received much attention as a possible material for thin film solar cells because of its superior optical absorption coefficient, making it viable for thin films (cell thickness < 1/*xm*). a-Si also provides cost-effective fabrication because of its low raw material requirements and low production energy requirements (deposition temperature < 300 °C). Today the best single crystal Si solar cells have reached an efficiency of 24.7% [28]. Commercial silicon solar cell modules are available with conversion efficiencies as high as 18%. Nowadays lot of research work is going on the development and fabricated of single crystal ribbon silicon, which is lower in cost than the high in quality, and these particular benefit has motivated the researchers in R&D for single crystal Si solar cells.

3.1.1.2. Polycrystalline silicon. Consisting of small grains of single-crystal silicon, polycrystalline PV cells are less energy efficient than those of the single-crystalline silicon PV cells. The grain boundaries in polycrystalline silicon, heddle the flow of electrons and hence, reduces the power output of the cell. The energy conversion efficiency for a commercial module made of polycrystalline silicon ranges between 10 and 14% [29]. A common approach to produce polycrystalline silicon PV cells is to slice thin wafers from blocks of cast polycrystalline silicon. Another advanced approach is the “ribbon growth” method in which silicon is grown directly as thin ribbons or sheets with the approach thickness for making PV cells. The most commercially developed ribbon growth approach is the edge-defined film-fed growth (EFG). Compared to single-crystalline silicon, polycrystalline silicon material is stronger and can be cut into one-third the thickness of a single-crystal material. It also has slightly lower wafer cost and less strict growth requirements. The average price for a polycrystalline module made from cast and ribbon is $3.92 per peak watt in 1996 (as per the literature survey), slightly lower than that of a single-crystal module [30].

3.1.1.3. Amorphous silicon. Amorphous silicon is a non-crystalline form of silicon, i.e. its silicon atoms are disordered in structure. Amorphous silicon (a-Si) PV modules were the first thin film PV modules commercially produced and presently the only thin film technology that has an impact on the overall PV markets. It was first discovered in 1974. A significant advantage of a-Si is its high (sunlight) absorptivity, about 40 times higher than that of single-crystal silicon. Therefore only a thin layer of a-Si is sufficient for making PV cells of about 1 μm thick as compared to 200 or more micrometers thick for crystalline silicon cells. Also, a-Si can be deposited on various low-cost substrates, including steel, glass and plastic, and the manufacturing process requires lower temperatures and hence, less energy input. So the total material costs and manufacturing costs are lower per unit area as compared to those of crystalline silicon cells [31,32].

3.1.2. III-V group solar cells

3.1.2.1. Gallium arsenide (GaAs). A compound semiconductor made of two elements: gallium (Ga) and arsenic (As), GaAs has a crystal structure similar to that of silicon. An advantage of GaAs is that it has high level of light absorptivity. To absorb the same amount of sunlight, GaAs requires only a layer of few micrometers thick while crystalline silicon requires a wafer of about 200–300 μm thick. It has a direct band gap of 1.43 eV, nearly ideal for single junction solar cells. The absorption coefficient of GaAs is relatively high and causes sufficient absorption of photons in only a few microns of material. The first AlGaAs/n-GaAs based solar cells with a reasonably high efficiency of 11% was reported by Alferov et al. [33]. Its high resistance to heat makes the ideal choice for concentrator systems in which cell temperatures are high. GaAs is also popular in space applications where strong resistance against solar radiation damage and high cell efficiency are required. The biggest drawback of GaAs PV cells is the high cost of the single-crystal substrate that GaAs is grown on. Therefore it is most often used in concentrator systems where only a small area of GaAs cells is needed [34].

3.1.2.2. Indium phosphide. Indium phosphide (InP) has a direct band gap of 1.34 eV, close to the optimum for solar conversion. The first InP solar cells were homo junction devices produced by thermal diffusion; however, subsequently a range of device structures was produced using different techniques. The first high-efficiency InP based devices were produced during the second half of 1970s [35]. The historical development of single junction InP based devices was reviewed in the 1989 [36]. An efficiency of 22% for an InP crystalline solar cell has already been reported in literature [37]. The disadvantage of using III-V compounds in photovoltaic devices is the very high cost of producing. Crystal imperfections, including unwanted impurities, severely reduce the device efficiencies and alternative lower cost deposition methods cannot be used. These materials are also easily cleaved and are significantly weaker, mechanically, than silicon. The high density of the materials is also a disadvantage, in terms of weight, unless very thin cells can be produced to take advantage of their high absorption coefficients. These drawbacks led to them being considered as unpromising materials for single junction, terrestrial, solar cells. It was primarily due to their potential for space applications that development of III-V based devices was undertaken. The potential for high conversion efficiencies together with radiation resistance in the demanding environment of space power generation mitigated against the high materials cost [27].

3.1.3. Thin films solar cells

In a thin-film PV cell, a thin semiconductor layer of PV materials is deposited on low-cost supporting layer such as glass, metal or plastic foil. Since thin-film materials have higher light absorptivity than crystalline materials, the deposited layer of PV materials is

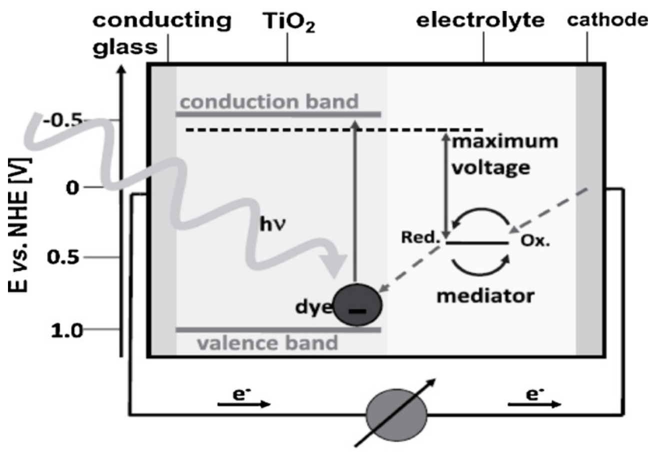

Fig. 8. Operating principles and energy level diagram of dye-sensitized solar cells.

extremely thin, from a few micrometers to even less than a micrometer (a single amorphous cell can be as thin as 0.3 μm). Thinner layers of material yield significant cost saving. Also, the deposition techniques in which PV materials are sprayed directly onto glass or metal substrate are cheaper. So the manufacturing process is faster, using up less energy and mass production is made easier to attractive approach of crystalline silicon. The conversion efficiency may be reduced but this would be more than balanced by the gain in power to weight ratio. A search for more suitable thin film materials revealed copper indium sulfide, cadmium telluride (CdTe) as well as copper indium diselenide ($CuInSe_2$) and its related alloy for the production of low cost thin film solar cells and they have been established as the most promising candidates for the next generation solar cells [38].

3.1.4. Dye-sensitized solar cells

Dye-sensitized solar cells (DSCS) have been widely investigated as a next-generation solar cell because of their simple structure and low manufacturing cost. The dye-sensitized solar cells (DSCs) provide a technically and economically credible alternative concept to present day p–n junction photovoltaic devices. Up to now, commercially available photovoltaic technologies are based on inorganic materials, which require high costs and highly energy consuming preparation methods [39].

3.1.4.1. Working principle. The actual dye-sensitized solar cell contains broadly five components: (1) a mechanical support coated with transparent conductive oxides; (2) the semiconductor film, usually TiO_2; (3) a sensitizer adsorbed onto the surface of the semiconductor; (4) an electrolyte containing a redox mediator; (5) a counter electrode capable of regenerating the redox mediator like platine. Titanium dioxide TiO_2 became the semiconductor of choice for the photo-electrode due to its multiple advantages, i.e. low cost, widely available, and non-toxic. Fig. 8 shows the operating principles of the dye-sensitized solar cell [40]. The first step is the absorption of a photon by the sensitizer, leading to the excited sensitizer which injects an electron into the conduction band of the semiconductor, leaving the sensitizer in the oxidized state. The injected electron flows through the semiconductor network to arrive at the back contact and then through the external load to the counter electrode to reduce the redox mediator which in turn regenerates the sensitizer. This completes the circuit. Under illumination, the device constitutes a regenerative and stable photovoltaic energy conversion system. Chiba et al. [41] investigated on dye-sensitized solar cells (DSCs) using titanium dioxide (TiO_2) electrodes with different haze. It was found that the incident photon to current efficiency (IPCE) of DSCs increases with increase in the haze of the TiO_2 electrodes, especially in the near infrared wavelength region. They found conversion efficiency of 11.1%, measured by a public test center. This indicates that raising the haze of TiO_2 electrodes is an effective technique for improvement of conversion efficiency.

4. Solar PV/thermal hybrid technology

A PV–thermal (PVT) collector is a module in which the PV is not only producing electricity but also serves as a thermal absorber. In this way both heat and power are produced simultaneously. Since the demand for solar heat and solar electricity are often supplementary, it seems to be a logical idea to develop a device that can comply with both demands. Photovoltaic (PV) cells utilize a fraction of the incident solar radiation to produce electricity and the reminder is turned mainly into waste heat in the cells and substrate raising the temperature of PV as a result, the efficiency of the module decreased. The photovoltaic/thermal (PV/T) technology recovers part of this heat and uses it for practical applications. The simultaneous cooling of the PV module maintains electrical efficiency at satisfactory level and thus the PV/T collector offers a better way of utilizing solar energy with higher overall efficiency.

There are alternative approaches in PVT integration. Among many others, there can be selections among air, water or evaporative collectors, monocrystalline/polycrystalline/amorphous silicon (c-Si/pc-Si/a-Si) or thin-film solar cells, flat-plate or concentrator types, glazed or unglazed panels, natural or forced fluid flow, standalone or building-integrated features, etc. A major research and development work on the PVT technology has been conducted in the past few years with a gradual increase in the level of activities. The attractive features of the PV/T system are [42]:

- it is dual-purpose: the same system can be used to produce electricity and heat output;
- it is efficient and flexible: the combined efficiency is always higher than using two independent systems and is especially attractive in building integrated PV (BIPV) when roof-panel spacing is limited;
- it has a wide application: the heat output can be used both for heating and cooling (desiccant cooling) applications depending on the season and practically being suitable for domestic applications;
- it is cheap and practical: it can be easily retrofitted/integrated to building without any major modification and replacing the roofing material with the PV/T system can reduce the payback period.

Different types of PV/thermal collector are being used presently such as, PVT/air, PVT/water and PVT concentrated collector [43]. The next section of this review article is focus on development of the PV/thermal technology and application.

4.1. Types for PV/thermal collector

PV/thermal devices can vary in design for various applications, PV/T domestic hot water systems, PV/T for air heating system for building actively cooled PV concentrators. The worldwide markets for both solar thermal and solar PV technology are growing rapidly and have reached a very substantial size. For PV/T a similar growth can be expected, since the technical feasibility is proven to be worth and can be integrated with other domestic applications.

PV/T has broad range of applications, that is, it is not only suitable for domestic hot water heating such as glazed PV/T collectors, but also for commercial buildings like ventilated PV to preheat air during winter for room heating and to provide the driving force for

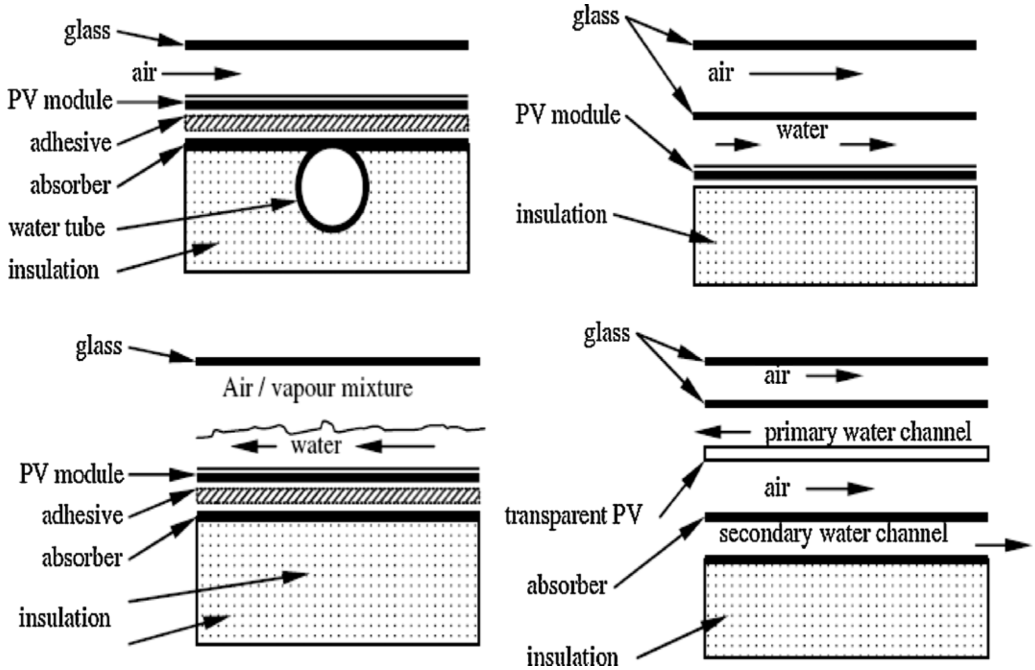

Fig. 9. Schematic diagram of a PV/T water collector.

natural ventilation during summer for thermal comfort/cooling/air circulation. There exist various forms of PV/T system, which depend on the type of PV module as well as its design, type of heat removal fluid (water/glycol or air) and on the concentration of the incoming radiation. Therefore, PV/T products can be classified as:

- liquid PV/T collector;
- air PV/T collector;
- PV/T concentrator.

4.1.1. Liquid PV/T collector

Similar to flat plate collector water heating system, liquid PV/thermal collectors are used to heat up the water and simultaneously electricity production for various domestic and industrial applications. The domestic water heater generally uses flat plate collectors in parallel connection and run automatically with the thermo-siphon action whereas the industrial water heating system a number of flat plate collectors in series are used and hence, it uses a photovoltaic driven water pump to maintain a flow of water inside the collector. A schematic diagram of a PV/T water collector is shown in Fig. 9.

Erdil et al. [44] did the experimental study on a hybrid system, composed of a photovoltaic (PV) module and a solar thermal collector and tested for energy collection at a particular geographical location in Cyprus (Fig. 10). Normally, it is required to install a PV system occupying an area of about 10 m^2 in order to produce electrical energy of 7 kWh/day, consumed by a typical household. In this experimental study, they used only two PV modules of area approximately 0.6 m^2 (i.e., 1.3 × 0.47 m^2) each. PV modules absorb a considerable amount of solar radiation that generate undesirable heat, which may be utilized in water pre-heating applications. The proposed hybrid system produces about 2.8 kWh thermal energy per day. Various attachments that are placed over the hybrid modules lead to a total of 11.5% loss in electrical energy generation. This loss, however, represents only 1% of the 7 kWh energy that is consumed by a typical household in the northern Cyprus. The pay-back period for the modification is less than 2 years. The low investment cost and the relatively short pay-back period makes this hybrid system economically attractive.

Chow et al. [45] has presented an experimental study of facade-integrated PV/T water-heating system and found the thermal efficiency as 38.9% and the corresponding electrical efficiency as 8.56% during the late summer in Hong Kong. They compared both forced as well as natural mode of water circulation and found that the latter is more preferable and suggested that this arrangement can serve as a water preheating system.

Fraisse et al. [46] studied the performance of water hybrid PV/T collectors to applied for direct solar floor type combine system. Its low operating temperature level is appropriate for the operating conditions of the mono- or poly-crystalline photovoltaic modules selected in that study. They concluded that the annual photovoltaic cell efficiency is 6.8% which represents a decrease of 28% in comparison with a conventional non-integrated PV module of 9.4% annual efficiency. This is obviously due to a temperature increase related to the cover. On the other hand, without a glass cover, the efficiency is 10% which is 6% better than a standard module due to the cooling effect. Further research led to water hybrid PV/T solar collectors as a one piece component, both reliable and efficient, and including the thermal absorber, the heat exchanger and the photovoltaic functions. Assoa et al. [47] presented the development of a new concept of photovoltaic/thermal (PV/T) collector. This type of collector combines preheating of the air and the production of hot water in addition to the classical electrical function of the solar cells. In this work, a simplified steady-state two-dimensional mathematical model of a PV/T bi-fluid (air and water) collector with a metal absorber is developed. A parametric study is undertaken to determine the effect of various factors including, the mass flow rate of water on the thermal performance of the solar collector. The experimental study carried out validates the simulated values, which were used in conceiving the final design of a prototype system. Besides, the parametric study also predicated the variation of the temperature of cells and the fluids as a function of the mass flow rate of water and air and the collector length. They found that mass flow rate of water in solar collector seems to have very little influence on the solar air collector behavior. However, some thermal losses exist between the solar air collector and the solar water collector. The solar collector performance study indicates that for a given specific collector length and mass flow rate of the fluid,

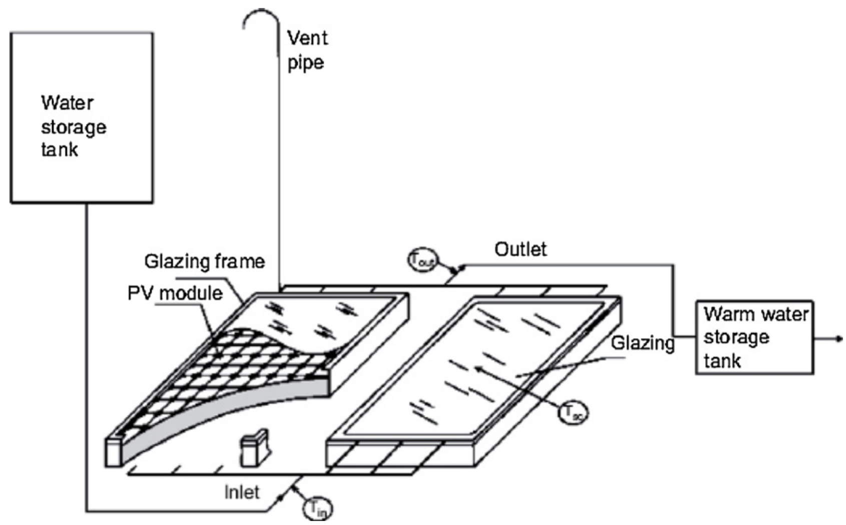

Fig. 10. Structure of the hybrid system.

the thermal efficiencies are able to reach approximately 80% and the cooling of the PV cells is satisfactory and can be improved. Using further simulation results they showed that the prototype is to be adapted for moderate temperature range appropriate for the production of domestic hot water besides, some solar cooling applications.

Kalogirou and Tripanagnostopoulos [48] developed the hybrid PV/T solar systems for domestic hot water and electricity production. When properly designed, the PV/T systems can extract heat from PV modules for water/air heating to reduce the operating temperature of the PV modules and hence, to keep the electrical efficiency at a sufficient desired level. Hybrid PV/T systems consisting of pc-Si and a-Si PV modules combined with water heat extraction units, were constructed and tested at the University of Patras as well as simulated with the TRNSYS program. The work includes the study of two PV/T systems, one with a small scale unit of $4\,m^2$ aperture area and 160 L water storage tank and another with a large scale system of $40\,m^2$ aperture area and 1500 L storage tank. The results showed that the electrical production of the system employing polycrystalline solar cells is higher than that of employing the amorphous ones, but the solar thermal contribution is slightly lower. The derived TRNSYS results give an account of the energy and cost benefits (Fig. 11) of the studied PV/T systems with both the thermosyphon and forced water flow. As a general conclusion, it can be said that as the overall energy production of the units

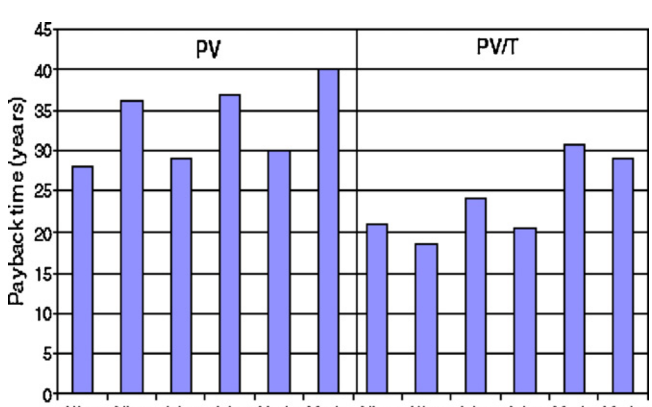

Fig. 11. Payback times of plain PV and thermosyphon PV/T systems with polycrystalline (p) and amorphous (a) silicon cells.

is increased, the hybrid units have better chances of success. This is also strengthened by the improvement of the economic viability of the systems, especially in applications where low temperature water, like hot water production for domestic use, is also required.

Tiwari et al. [49] carried out the analytical study for the prediction of water temperature of an integrated photovoltaic thermal solar (IPVTS) water heater under constant mass flow rate. They [46] carried out the analysis using basic energy balance for hybrid flat plate collector and storage tank, in the terms of design and climatic parameters respectively. It is observed that the daily overall thermal efficiency of IPVTS system increases with increasing the constant mass flow rate of the circulating fluid but collection temperature decreases. The exergy analysis of IPV/TS system has also been carried out. It is further to be noted that the exergy and thermal efficiency of an integrated photovoltaic thermal solar system (IPVTS) is maximum at the hot water withdrawal flow rate of 0.006 kg/s. The hourly net electrical power available from the system has also been evaluated.

Touafek et al. [50] presented the experimental study on a new hybrid photovoltaic thermal collector. They proposed a new approach of design, aiming to increase the energy effectiveness of electric and thermal conversion with lowest cost as compared to the conventional hybrid collector technology already existing. The experimental results approximately similar to the theoretical ones, show that the thermal performance of the new hybrid collector has improved as compared to the classic hybrid PV–T solar collectors. Dubey and Tiwari [51] evaluated the performance of partially covered flat plate solar collectors for water heating connected in series using theoretical modeling and a PV module is used to run the DC motor to circulate water. It is observed that the collectors partially covered by PV module combines the production of hot water and electricity generation and it is beneficial for the users whose primary requirement is hot water production while the collectors can be fully covered by PV specially for the users whose primary requirement is electricity generation. They have also found that if this type of system is installed only in 10% of the total residential houses in Delhi (India) then the total carbon credit earned by PV/T water heaters in terms of thermal energy is about 44.5 millions US $ per annum and in terms of exergy it is 14.3 millions US $ per annum, respectively.

Fraisse et al. [46] also studied the energy performance of water hybrid PV/T collectors (Fig. 12). The integration of photovoltaic (PV) modules in buildings allows one to consider a multifunctional frame and then to reduce the cost by substitution of components.

Fig. 12. The glass covered water PVT prototype.

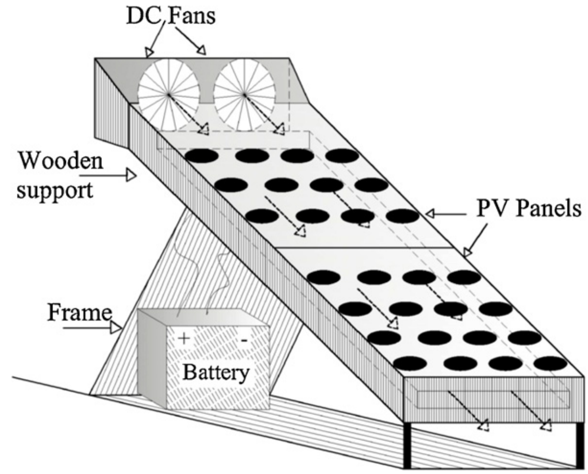

Fig. 13. Schematic of the prototype pf PV/thermal air collector.

In order to limit the rise of the cell operating temperature, a photovoltaics/thermal (PV/T) collector combines solar water heating system and PV cells. The recovered heat energy can be used for various heating applications including water heating. In this study, the poly-crystalline photovoltaic modules of 16 m^2 and 16 m^2 of solar thermal collector were selected. They have also replaced two conventional collectors by one hybrid PVT collector with a varying area from 16 to 32 m^2.

4.1.2. PV/T air collector

Air and water both have been used as heat transfer fluids in practical PV/T solar collectors, yielding PVT/air and PVT/water heating systems respectively. PVT/water systems are more efficient than those of PVT/air systems [52] due to the high thermo-physical properties of water as compared to air, However, PVT/air systems (Fig. 13) are utilized in many practical applications due to low construction (minimal use of material) and operating cost among others.

Aste et al. [53] designed and performance evaluated of a hybrid PVT air collector. They designed a PV module integrated in common sloped roofs or vertical facades, replacing the external covering, water proofing and insulation layers. The schematics of the PVT collector are shown in (Fig. 14). The upper cover of system was covered by a glass sandwich type PV cells. The cell area can cover the entire glazed surface or can be distributed in a grid where the spacing between adjacent columns and rows can allow a direct gain of solar radiation to the backward absorber plate. The glass sandwich looks like a chessboard composed of squares with or without PV cells embedded. The simulation model, developed predicts quite well the thermal and electrical performance of a PVT collector.

Tonui and Tripanagnostopoulos [54] worked for air-cooled PV/T solar collectors with low cost performance improvements. They investigated the performance of two low cost heat extraction improvement modifications in the channel of a PV/T air system to achieve higher thermal output and PV cooling so as to keep the electrical efficiency at acceptable level. The use of thin flat metal sheet suspended at the middle or the finned back wall of an air channel in the PV/T air configuration has been suggested. A theoretical model is developed and validated against experimental data, where good agreement between the predicted results and measured data were achieved. The validated model was then used to study the effect of the channel depth, channel length and mass flow rate on electrical and thermal efficiency, PV cooling and pressure drop for both improved and typical PV/T air systems and the results were compared.

Sukamongkol et al. [55] presented an experimental test to predict the dynamic performance of a condenser heat recovery with a photovoltaic/thermal (PV/T) air collector to regenerate desiccant for reducing energy use of an air conditioning room in tropical climates. The system consists of five main parts; namely, living space, desiccant dehumidification and regeneration unit, air conditioning system, PV/T collector, and air mixing unit. The results of this experiment show that the thermal energy generated by the system can produce warm dry air as high as 53 °C and 23% relative

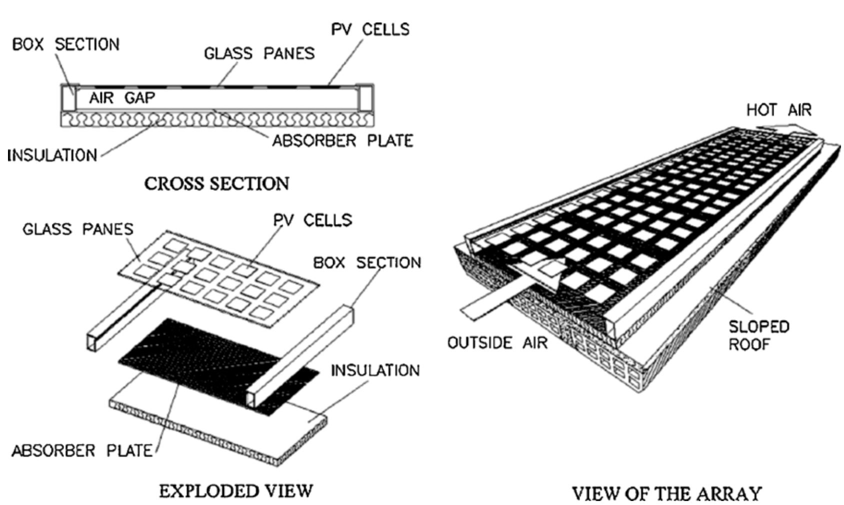

Fig. 14. Preliminary sketches of the PVT collector.

humidity. Additionally, electricity of about 6% of the daily total solar radiation can be obtained from the PV/T collector in the system. Moreover, the use of a hybrid PV/T air heater, incorporated with the heat recovered from the condenser to regenerate the desiccant for dehumidification, can save the energy use of the air conditioning system by approximately 18%.

Sarhaddi et al. [56] investigated the thermal and electrical performance of a solar photovoltaic thermal (PV/T) air collector. The thermal and electrical parameters of a PV/T air collector include solar cell temperature, back surface temperature, outlet air temperature, open-circuit voltage, short-circuit current, maximum power point voltage, maximum power point current, etc. The electrical model presented can estimate the electrical parameters of a PV/T air collector such as open-circuit voltage, short-circuit current, maximum power point voltage, and maximum power point current, etc. Furthermore, an analytical expression for the overall energy efficiency of a PV/T air collector is derived in terms of thermal, electrical, design and climatic parameters. The results of numerical simulation show good agreement with the experimental measurements. They found that the thermal efficiency, electrical efficiency and overall energy efficiency of PV/T air collector is about 17.18%, 10.01% and 45%, respectively, for a typical climatic, operating and design parameters.

Hegazy [57] made the overall performance of flat plate photovoltaic/thermal (PV/T) air collectors for thermal, electrical and hydraulic parameters. Four popular designs were considered with the air flowing either over the absorber (Model I) or under it (Model II) and on both sides of the absorber in a single pass (Model III) or in a double pass (Model IV). Heat balance equations written for each model have been solved numerically, incorporating/using the measured climate data. The effects of air specific flow rate and the selectivity of the absorber plate and PV cells on the performances have been examined. They [54] found that under similar operational conditions, Model I has the lowest performance, while the other models exhibit better thermal and electrical output gains as compared to Model I. Nevertheless, Model III demands the least fan power, followed by Models IV and II respectively. They also showed that the selective properties are inappropriate for these PV/T collectors due to the reduction in the generated energy by PV, especially at low flow rates. Beccali et al. [58] presented a detailed analysis of the energy and economic performance of desiccant cooling systems (DEC) equipped with both single glazed standard air and hybrid photovoltaic/thermal (PV/T) collectors for applications in hot and humid climates. They showed the detailed results of simulations conducted for a set of desiccant cooling systems operating without any heat storage. System performance was investigated through hourly simulations for different systems and load combinations. Two kinds of building occupations were considered, viz. office and lecture room. Moreover, three configurations of solar-assisted air handling units (AHUs) equipped with desiccant wheels were considered and compared with standard AHUs, focusing on achievable primary energy savings. The relationship between the area of solar collector's and the specific primary energy consumption for different system configurations and building occupation patterns has been described. An outcome of their work is that solar air-cooling (SAC) systems equipped with PV/T collectors are shown to have better performance in terms of primary energy saving than that of the conventional systems fed by vapor compression chillers and coupled with PV cells. All solar air-cooling systems present good figures of merit for the primary energy consumption but the best performances is seen in systems with integrated heat pumps and small solar collector areas.

4.1.3. PV/T concentrator

Concentrating photovoltaic (CPV) systems can operate at higher temperatures than those of the flat plate collectors. Collecting the rejected heat from a CPV system leads to a CPV/thermal (CPV/T) system, providing both electricity and heat at medium temperatures. The use of CPV/T in combination with concentrating reflectors has a significant potential to increase the power production from a given solar cell area. Presently, research is going to develop CPV/T collector for more electricity as well as heat generation. Few authors have worked in this direction enabling the multipurpose hybrid systems to fulfill the increasing demand of both electrical and thermal energy, while protecting the environment.

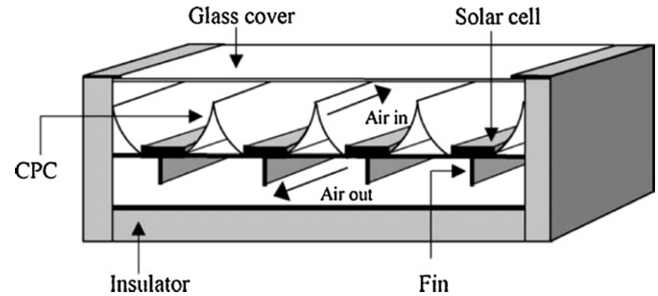

Fig. 15. The schematic model of a double-pass photovoltaic thermal solar collector with CPC and fins.

Hjothman et al. [59] designed and fabricated a double-pass photovoltaic thermal solar air collector with CPC and studied the performance over a range of operating conditions. The absorber of the hybrid photovoltaic/thermal (PV/T) collector consists of an array of solar cells for generating electricity, compound parabolic concentrator (CPC) to increase the radiation intensity falling on the solar cells and fins attached to the back side of the absorber plate to improve heat transfer rate to the flowing air. The basic components of the experimental setup are as follows (Fig. 15). (a) Double-pass photovoltaic/thermal solar collector, (b) the air flow measurement system, (c) the temperature measurement system, (d) the wind speed measurement system, (e) the current and voltage measurement system, (f) the solar radiation measurement system and (g) the data acquisition system. The results showed that electricity production in a PV/T hybrid module decreases with increasing the temperature of the airflow. This implies that the air temperature should be kept as low as possible. On the other hand, the system should deliver hot air for other purposes. A trade off between maximizing electricity and production of hot air at reasonable high temperatures is thus necessary. The simultaneous use of hybrid PV/T, CPC and fins have a potential to significantly increase the power production and reduce the cost of photovoltaic electricity.

Kostic et al. [60] designed the optimal orientation of PV/T collector with reflectors. In order to get more thermal and electrical energy, flat reflectors for solar radiation have been mounted on PV/T collector. To obtain higher solar radiation intensity on PV/T collector, they designed reflectors with the movable PV/T collector system (Fig. 16). In this work, the thermal and electrical efficiency of PV/T collector without reflectors and with reflectors in optimal position have been calculated. Using the experimental results, the total efficiency and energy-saving efficiency of PV/T collector have been determined. Energy-saving efficiency for PV/T collector without reflectors is found to be 60.1%, which is significantly higher than for the conventional solar thermal collector. On the other hand, the energy-saving efficiency for PV/T collector with reflectors in optimal position is found to be 46.7%, which is almost equal to the thermal efficiency of a conventional solar thermal collector. The energy-saving efficiency of PV/T collector decreases slightly with the solar radiation intensity concentration factor.

Coventry [61] designed a parabolic trough photovoltaic/thermal collector with a geometric concentration ratio of 37 X at ANU Australia as shown in (Fig. 17). The thermal and electrical efficiencies of the ANU CHAPS collector are shown under ideal conditions. A

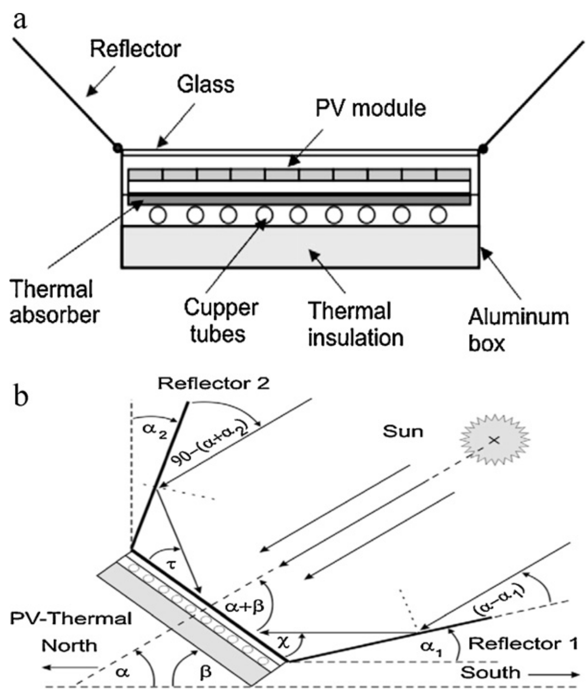

Fig. 16. (a) Schematic diagram of the cross section of PV/T collector. (b) Schematic diagram of the PV/T collector with solar radiation reflectors.

comparison was made with a flat plate thermal collector that shows that the CHAPS collector has a lower efficiency at temperatures near ambient (due to optical losses). It does not suffer the rapid increase in thermal losses as the operating temperature increases, due to the much reduced surface area. Measured results under typical operating conditions showed that the thermal and electrical efficiencies are found to be around 58% and 11% respectively, therefore a combined efficiency of 69% which is significantly high enough.

Kribus et al. [62] analyzed a novel miniature concentrating photovoltaic (MCPV) system. A miniature concentrator PV/thermal system is under development, producing about 140–180 W of electricity and an additional 400–500 W of heat. Unlike the PV/thermal (PV/T) collectors, the heat from an MCPV collector is not limited to low-temperature applications. The later system can operate over a wide range of temperatures, and provide thermal energy not only for water heating, but also for cooling, desalination, and industrial process heat. An analysis of the system performance has shown that at elevated temperatures, the electrical efficiency is somewhat lower, but most of the lost electricity is recovered as thermal energy. The MCPV system is suitable for installation close to a consumer where there is a need for multiple forms of energy such as, electricity, heat and cooling. The results showed that the new approach has promising prospects in the increasing demand of energy with clean development.

Fig. 17. Prototype CHAPS collector at the ANU.

5. Novel applications of PV/thermal collector

PV/thermal collector has good potential for some other applications such as solar cooling, water desalination, solar greenhouse, solar still, photovoltaic–thermal solar heat pump/air-conditioning system, building integrated photovoltaic/thermal (BIPVT) solar collector. Developments in the PV/thermal collector system are discussed as below.

Mittelman et al. [63] designed a solar cooling with concentrating photovoltaic/thermal (CPVT) systems. They presented a combined heat and power approach that employs high performance CPVT technology in order to produce both electricity and thermal energy at low or medium temperatures. The possible range of temperatures have been found to be wide enough to satisfy the requirements of several attractive thermal applications for both domestic and industrial use. The CPVT collectors may operate at temperatures above 100 °C, and the thermal energy can drive several useful processes such as refrigeration, desalination and steam production. The performance and cost of a CPVT system with single effect absorption cooling are investigated in detail. They coupled to the CPVT collectors, a single effect absorption chiller, was analyzed under different scenarios. The results show that under a reasonably wide range of conditions, the CPVT cooling system can be comparable in costs to a conventional cooling system. Under some conditions, the solar cooling is even significantly less expensive than that of the conventional cooling system. This is in contrast with solar cooling using solar thermal collectors, which is usually found to be significantly more expensive than the conventional cooling system.

Mittelman [64] designed the desalination with the concentrating photovoltaic/thermal (CPVT) systems also. The combined system produces solar electricity and simultaneously exploits the waste heat of the photovoltaic cells to desalinate water. The results indicate that this approach can be competitive relative to other solar-driven desalination systems and even relative to conventional reverse osmosis (R.O.) desalination. The result depends on the economic conditions, and is valid when the prevailing price of electricity is high enough, and the installed cost of the solar collectors is low enough. The cost target for the solar collectors was defined in the suitable conditions, which lies comfortably within the acceptable range which the CPVT developers would like to achieve in the near future. Some of the economic scenarios have led to results of zero cost of the desalinated water. This indicates a potential for highly profitable cogeneration plants that can operate under market conditions without any incentive government. The main conclusion is then that the cost-effective cogeneration of electricity and desalinated water is feasible, and may become practical in the near future. A comparison of several solar desalination approaches has shown that R.O. with solar electricity from a PV plant is usually one of the best solar options in the non-competitive range, i.e., where solar desalination is still more expensive than that of the conventional desalination.

Nayak and Tiwari [65] describe the energy and exergy analysis for the prediction of performance of a photovoltaic/thermal (PV/T) collector integrated with a greenhouse at Indian Institute of Technology, Delhi, India. The analysis was based on quasi-steady state

Fig. 18. Photograph of experimental setup of hybrid (PV–T) active solar still.

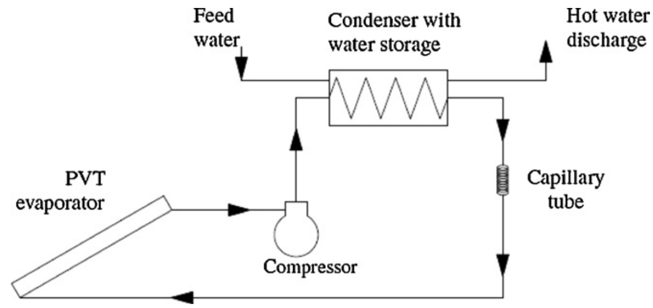

Fig. 19. Schematic diagram of the photovoltaic-integrated solar heat pump (PV-SAHP) system.

condition. Experiments have been conducted extensively during the period from June 2006 to May 2007, for the annual performance of the system. The numerical computation was carried out for typical day only for validation the experimental result obtained for the same period. They observed that the theoretical value of solar cell, back surface and greenhouse room air temperatures is approximately equivalent to the experimental values. The predicted and measured values of solar cell, back surface and greenhouse air temperatures have been verified in terms of the root mean square of percent deviation (7.05–17.58%) as well as the correlation coefficient (0.95–0.97) and both exhibit a fair agreement between them. Exergy analysis calculations of the PV/T integrated greenhouse system showed the second efficiency of approximately 4%. Rahul and Tiwari [66] also carried out the experimental and theoretical validation of a hybrid (PV–T) active solar still. The experimental set up (Fig. 18) consists of a single slope solar still of basin area 1 m × 1 m inclined at 30° connected with two flat plate collectors (each with an area of 1 m × 2 m, inclined at 45°). These FPCs are connected in series with a total effective area of 4 m^2 by using an insulated galvanized iron pipe of diameter 1.25 cm. A flat plate collector is used to increase the temperature of water in the solar still. One of the FPC is also integrated with a PV module (glass–glass) of 75 W at its lower temperature zone to run a DC motor used for water circulation.

Fang et al. [67] did an experimental study on the operation performance of a photovoltaic–thermal solar heat pump/air-conditioning system. The performance parameters, such as the evaporation pressure, the condensation pressure and the coefficient of performance (COP) of heat pump/air-conditioning system, the water temperature and receiving heat capacity in water heater, the photovoltaic (PV) module temperature and the photovoltaic efficiency have been investigated. The experimental results showed that the mean photovoltaic efficiency of a photovoltaic–thermal (PV/T) solar heat pump/air-conditioning system reaches 10.4%, and can enhance 23.8% in comparison to that of a conventional photovoltaic module. On the other hand, the mean COP of heat pump/air-conditioning system may attain 2.88 and the water temperature in water heater can increase to 42 °C. These results indicate that the photovoltaic–thermal solar heat pump/air-conditioning system has better performances can work with stability for such useful and potential applications, here by reducing the green house gases, enabling a clean environment.

Chow et al. [68] designed a PVT heat pump system for Hong Kong. They proposed a photovoltaic-integrated solar heat pump (PV-SAHP) system, which can be seen as a scientific merge of the photovoltaic/thermal and solar assistant heat pump technology, as a sustainable alternative (Fig. 19). It was found that the proposed system with R-134a as the refrigerant is able to achieve an yearly-average COP of 5.93 and PV output efficiency of 12.1%. Thus, the energy output is therefore considerably higher than that of the conventional heat pump plus PV "side-by-side" system. Within a year, the PV-SAHP system would have a better performance in summer time from May to October, when the monthly average COP could reach up to 6 or higher. In July as compared to January, the monthly average values of COP were found to be 6.89 and 5.05 respectively. The amount of hot water produced in summer could be more than double of that in the winter. As there is a continuous and constant demand of hot water in Hong Kong through the year in all type of building, and hence, the PV-SAHP system has the potential applications.

Anderson et al. [69] integrated photovoltaic/thermal (BIPVT) solar collector with building. In this study, the design of a novel building integrated photovoltaic/thermal (BIPVT) solar collector has been theoretically analyzed using a modified Hottel-Whillier model. This model was validated with the experimental data from the testing facility on a prototype BIPVT collector. The results showed that the key design parameters such as the fin efficiency, the thermal conductivity between the PV cells and their supporting structure, and the lamination method had a significant influence on both the electrical and thermal efficiency of the BIPVT. Furthermore, it was shown that the BIPVT could be made of lower cost materials, such as pre-coated color steel, without significant decreases in efficiency. Finally, there appears to be a significant potential to utilize the low natural convection heat transfer in the attic at the rear of the BIPVT system to act as an insulating layer rather than using additional insulation material. The use of such air would reduce the material cost of such a system to be significantly.

Davidsson et al. [70] developed and evaluated a building-integrated multifunctional PV/T solar window, which is constructed of PV cells laminated on solar absorbers placed in a window behind the glazing (Fig. 20). To reduce the cost of the solar electricity, tiltable reflectors were introduced in the construction to focus radiation onto the solar cells. The reflectors render the possibility of controlling the amount of radiation transmitted into the building. The insulated reflectors also reduce the thermal losses through the window. A model for simulation of the electric and hot water production was developed which can perform the yearly energy simulations for different features, such as the shading of the cells and/or effects of the glazing can be included or excluded. The simulation can be run with the reflectors in an active, passive, up right and horizontal positions. The simulation program has been calibrated against the measurements on a prototype solar window placed in Lund, south of Sweden and against a solar window built into a single family house at Solgarden, central part of Sweden. The results from the simulation showed that the solar

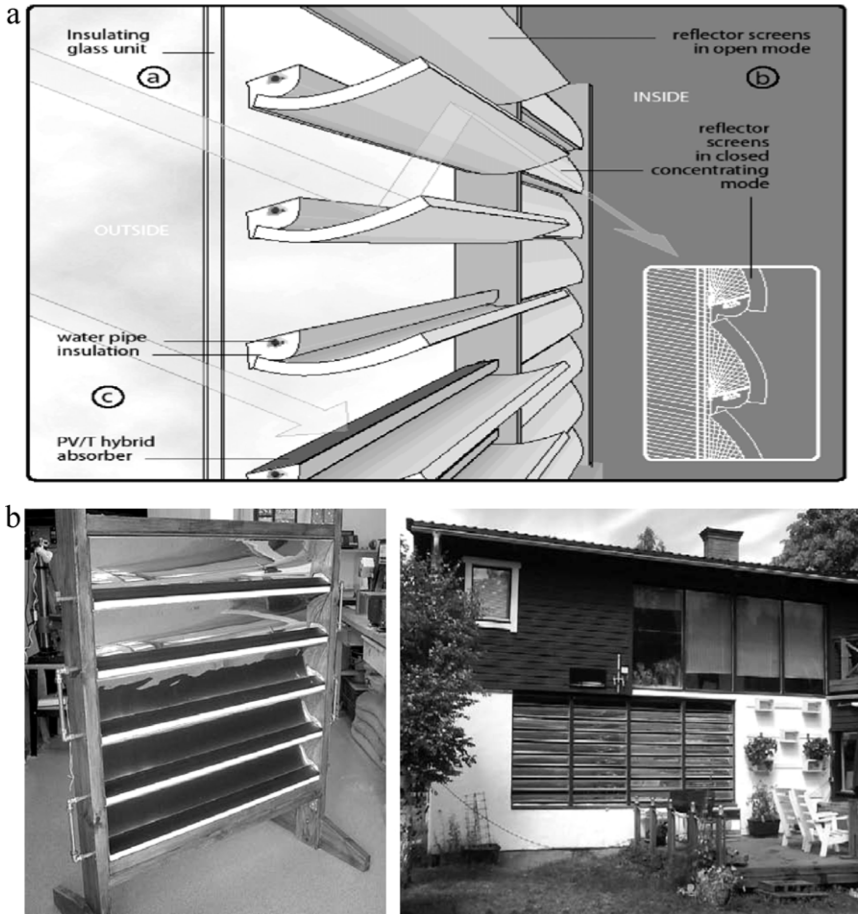

Fig. 20. (a) Solar window at Lund in the south of Sweden. (b) Left: the prototype solar window; right: the solar window in Solgarden, Sweden with closed reflectors.

window annually produces about 35% more electric energy per unit cell area as compared to a vertical flat PV module.

Nagano et al. [71] developed the experimental thermal–photovoltaic (PV) hybrid exterior wallboards that incorporate of PV cells. The clapboard-shaped hybrid wallboards permit modular assembly that can be more easily adapted for building applications than previous PV systems as can be seen in Fig. 21. Solar heat is collected in the form of heated air circulating in the air gap between the hybrid wallboard and the thermal insulation of the exterior walls. These work presented an evaluation of both the electrical power generating ability and the solar heat collection capacity during winter with the six different variations of the experimental (thermal–PV hybrid wallboard) system and some of them are given as below:

1. Six variations of this wallboard were made using either amorphous or polycrystalline silicon PV modules, either with or without a glass plate enclosing the front face of the wallboard.
2. The average conversion efficiency based on the solar radiation at an inclination angle of 80° and the total cell area of 11.2% and 11.4% for wallboards PV3 and PV5, respectively: polycrystalline silicon modules and no glass plate covering the wallboard.
3. The average thermal collector efficiency based on perpendicular projected wall area and vertical global solar radiation ranged from 20.2% to 22.3% for wallboards without glass covers and from 29.2% to 36.9% for those with glass covers at 0 °C temperature of the ambient air. These efficiencies were found to be satisfactory for a structure as simple as this hybrid wallboard.

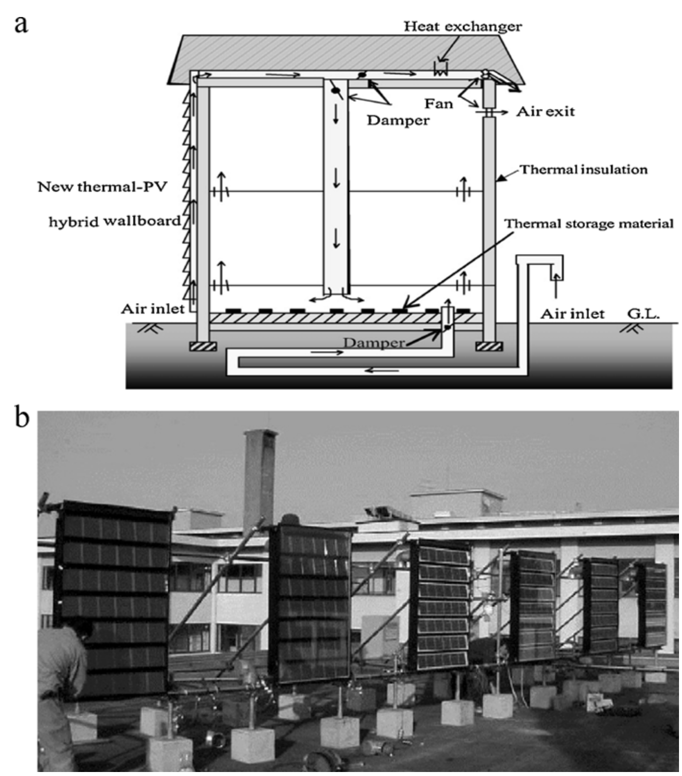

Fig. 21. (a) System concept of new type PV/T hybrid wallboard. (b) Six types of thermal–PV hybrid wallboards.

6. Conclusions

The present work is an overview of a rigorous study carried out by number of authors for the last 30 years, in the area of design, development, fabrication, and experimental evaluation of various combinations of the photovoltaic/thermal (PVT) hybrid technology for different useful and applied application. The hybrid photovoltaic/thermal (PV/T) systems consist of PV modules and heat extraction units mounted together. These systems can simultaneously provide electrical and thermal energy, thus achieving a higher energy conversion rate of the absorbed solar radiation than that of a simple photovoltaic system. Different types of thermal collector and new material for PV cells have been developed for efficient renewable energy utilization. The solar energy conversion in electricity and heat with a single device is a good advancement for future energy demand called hybrid photovoltaic thermal collector (PVT).

The demand of heat and electricity are needed in industries and different application, i.e. solar cooling, water desalination, solar greenhouse, solar still and solar heat pump. Industries show high demand of energy for both heat and electricity and the hybrid PV/T systems could be used to meet the increasing energy demand for these requirements. This article gives the trends of development and technological advancement for the useful applications of PV/T of hybrid systems, like solar cooling, water desalination, solar greenhouse, solar still, photovoltaic–thermal solar heat pump/air-conditioning system, building integrated photovoltaic/thermal (BIPVT) solar collector and so on. The work done by different researchers in this area shows that there is a huge potential of new and hybrid solar energy devices for useful and multipurpose applications.

In hot countries, PV cells are suffering to low efficiency due non availability of low ambient temperature for cooling the PVC system. Thus, by placing a solar thermal collector behind a solar photovoltaic (PV) array, the PV cells can be cooled up some extent and at the same time the heat produced by a PVC system. At the same time, the solar collector can harvest most of the energy that passes through the array that would otherwise be lost, recovering it for productive and useful applications. In this scenario, the PV cells can be cooled by circulating fluid like water or air within the solar thermal collector and hence, the heat produced by PVC can be utilized in an optimum operating temperature range by controlling the flow rate of the cooling medium/circulation fluid.

As a general conclusion, it is clear from the literature review that PV/T collectors are very promising devices and that no substantial steps have been taken towards reducing their cost and making them more competitive. The overall energy production of the units is increased the hybrid system have better chances of success. Future work should be focus to improvement the efficiency of PV/T collectors and cost reduction, through this achievement, it will be more competitive collector device.

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